Keck Interferometer - Progress Report

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Outline

- Introduction
- Science with Keck Interferometer
- Instrument description
- Observing approach

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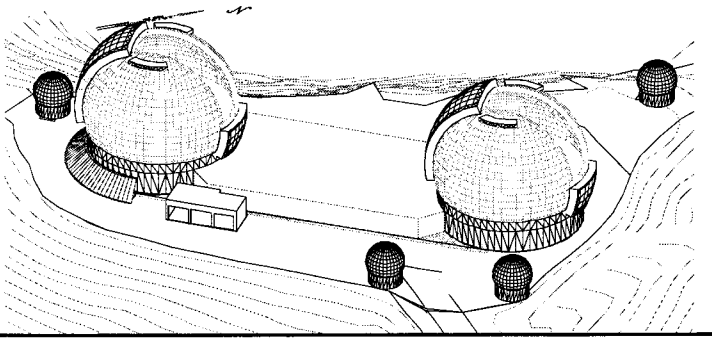
Keck Interferometer

- Interferometry with the two 10-m Keck telescopes on Mauna Kea and four 1.8-m outrigger telescopes
- NASA-funded joint project between JPL and CARA
- Five-year development; funding started FY98
- Broad range of science capabilities



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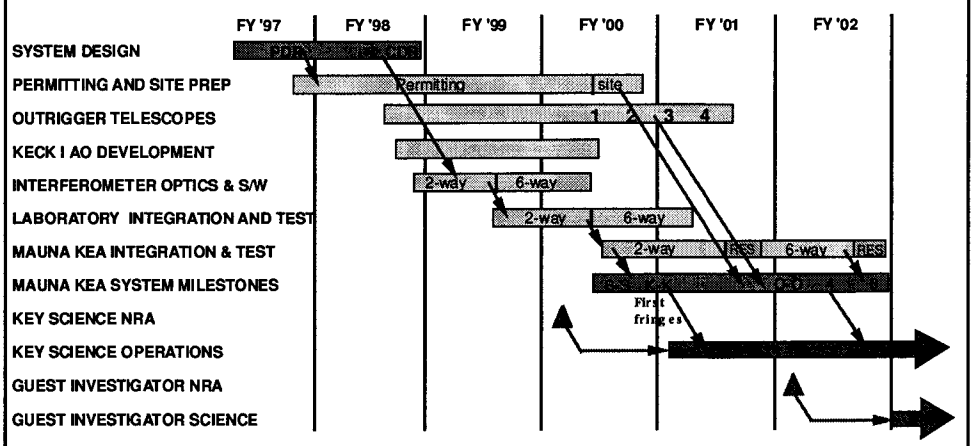
Schedule



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Key Features

- Michelson combination among two 10-m Kecks and four 1.8-m outrigger telescopes
  - Keck-Keck baseline: 85 m
  - Outrigger-outrigger baseline: 30 m (min) / 140 m (max)
- Phasing with adaptive optics and fast tip/tilt correction
- Cophasing with fringe detection/tracking and active delay lines
  - Dual-star feeds at each telescope
- Back-end instruments
  - Two-way beam combiners at 1.5--2.4 μm for fringe tracking (cophasing), astrometry, and imaging
  - Multi-way imaging combiner at 1.6--5 μm
  - Nulling combiner at 10 μm

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Science Using the Two Kecks

- Detection of hot Jupiters
  - Uses two-color differential-phase technique
- Characterization of exozodiacal dust
  - Survey a number of nearby systems for integrated exozodiacal emission at 10 μm
  - Data to be used for Terrestrial Planet Finder (TPF) mission planning
- High sensitivity parametric imaging

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Science Using the Kecks and Outriggers

- Astrometric search for planets
  - Survey 100's of nearby stars for planets to Uranus mass
  - Uses outrigger telescopes for long-term survey
- Imaging with 6-element array
  - Good (u,v)-plane coverage
  - 9 of 15 baselines include a 10-m telescope
    - » Background-limited sensitivity equivalent to two 4.4-m's
    - » Other imaging options using 1 Keck with outriggers, or just outriggers

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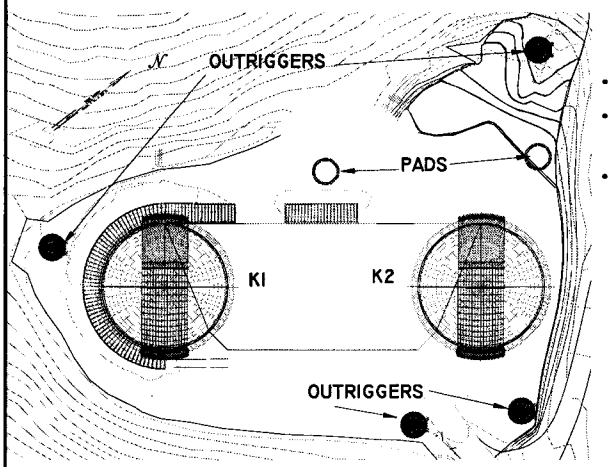
Site Plan



- 4 outrigger telescopes
- 2 additional outrigger pads (for future expansion)
- Underground pipes for light propagation to Keck basement

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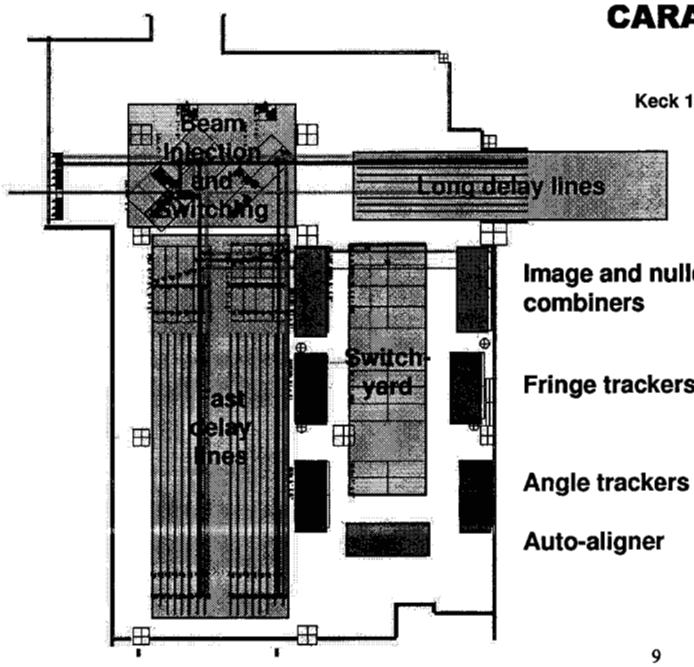
Basement Layout



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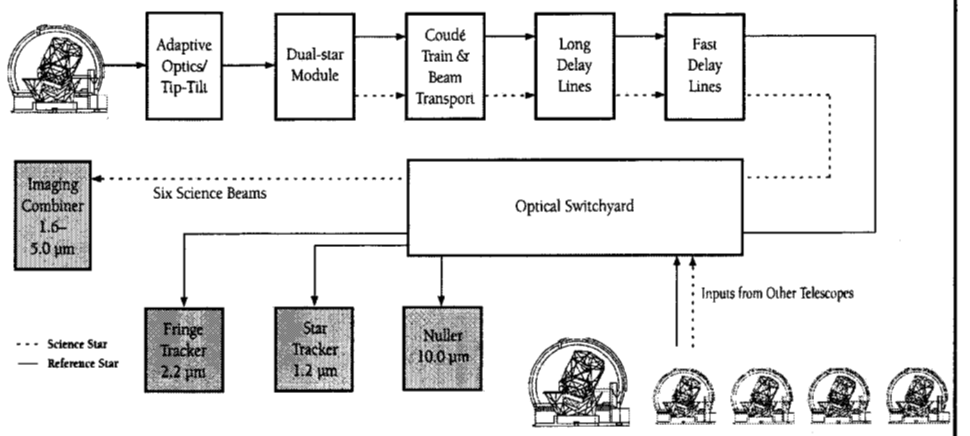
Keck Interferometer Beam Train



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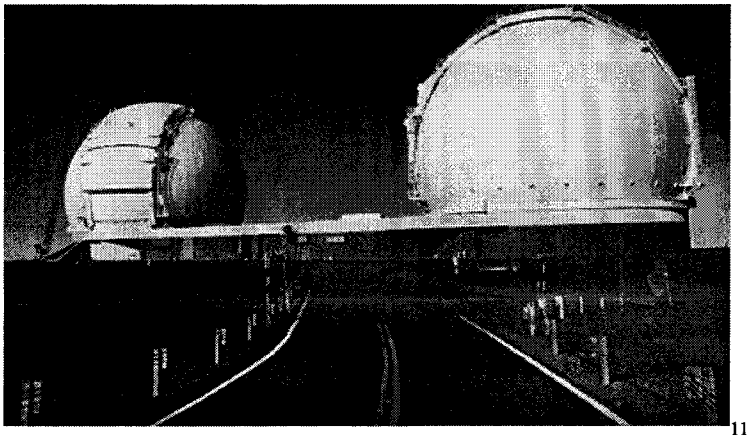
Telescopes

- Two 10-m Keck telescopes
  - 85-m Keck-Keck baseline



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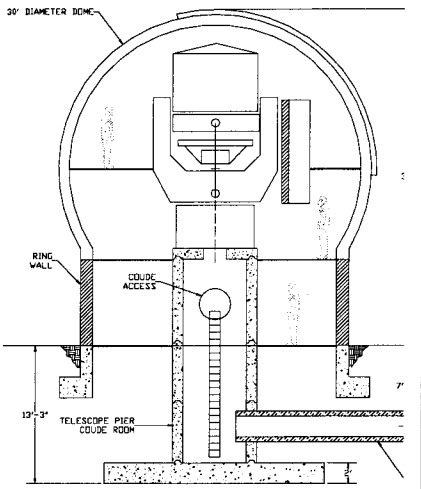
Telescopes

- Four 1.8-m outrigger telescopes
  - Used with Kecks for imaging
  - Used separately for astrometry
  - Key specifications
    - » 10-cm collimated output (after DSM)
    - » Stable pivot for astrometry
- For instrument debugging, 40-cm siderostats (like on PTI) will be used



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Siderostats

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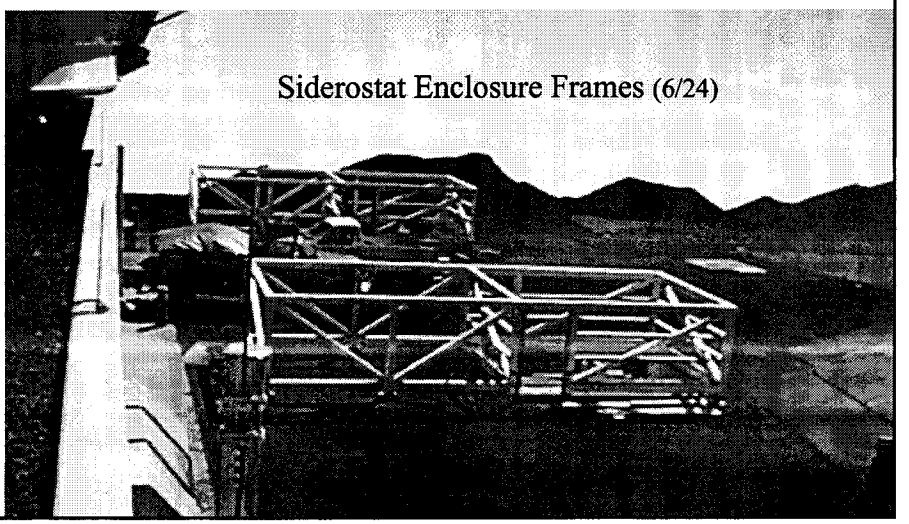
- Site work complete (tunnel, junction boxes, light pipes & enclosures are complete)
- Roll-off roofs to arrive in Sept.



Siderostat Enclosure Frames (6/24)

Siderostats

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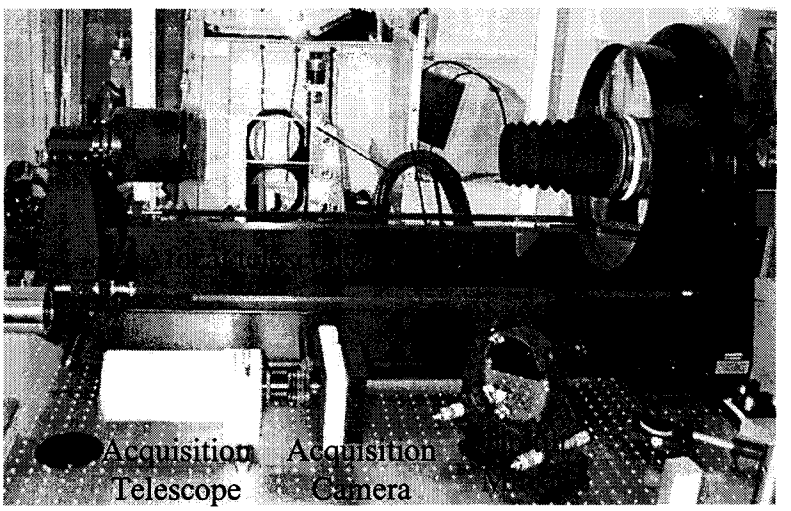
- All hardware ordered & most received.
  - Siderostat gimbal #1 acceptance test completed



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Wavefront Correction

- **Adaptive optics on the Kecks**
  - CARA, with funding from the Keck Foundation, is developing an Adaptive Optics system for Keck-2
  - With NASA funding, a second AO system will be added for Keck-1
  - Results of CARA's development of the Keck-2 system follow
- **Tip/Tilt correction on outriggers**
  - Fast tip/tilt is adequate for near-IR operation
  - Correction via active secondary
  - Sensing in beam-combining lab

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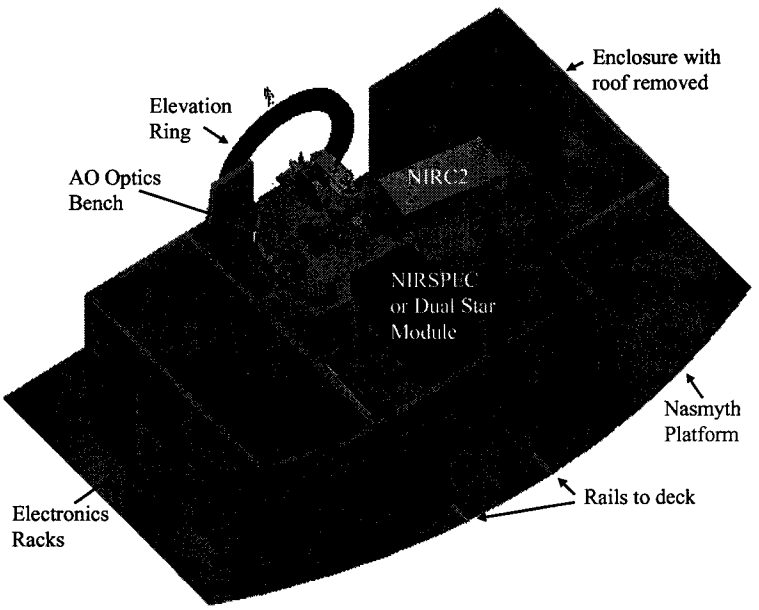
Keck II Left Nasmyth Platform



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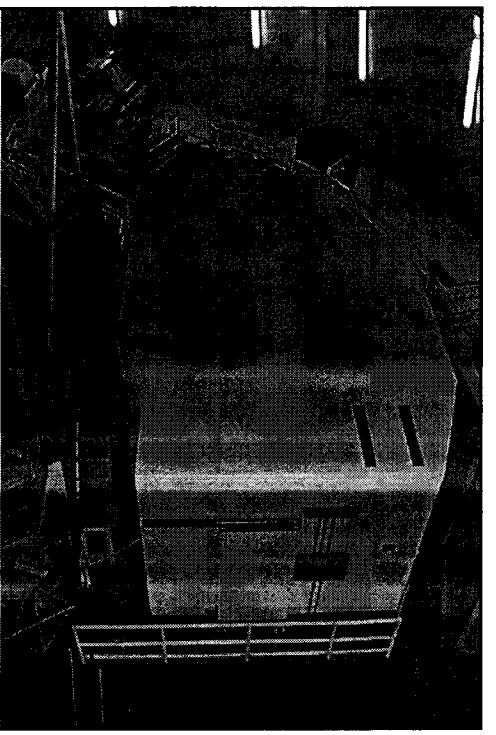
Nasmyth Platform Enclosure

Keck II Left Nasmyth



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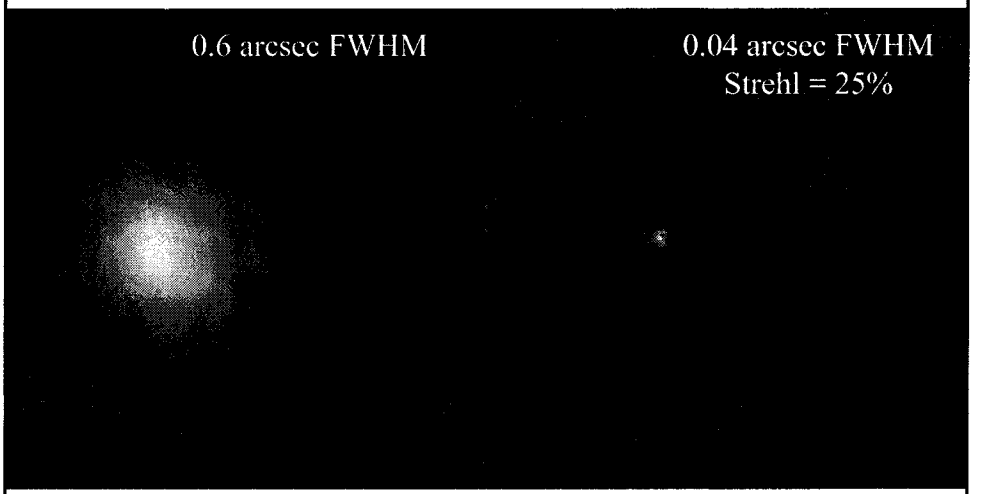
First Light Image

Uncorrected star image (V=5.8)

Keck AO corrected image



H-band images (autoscaled to peak) - 4.5 arcsec FOV

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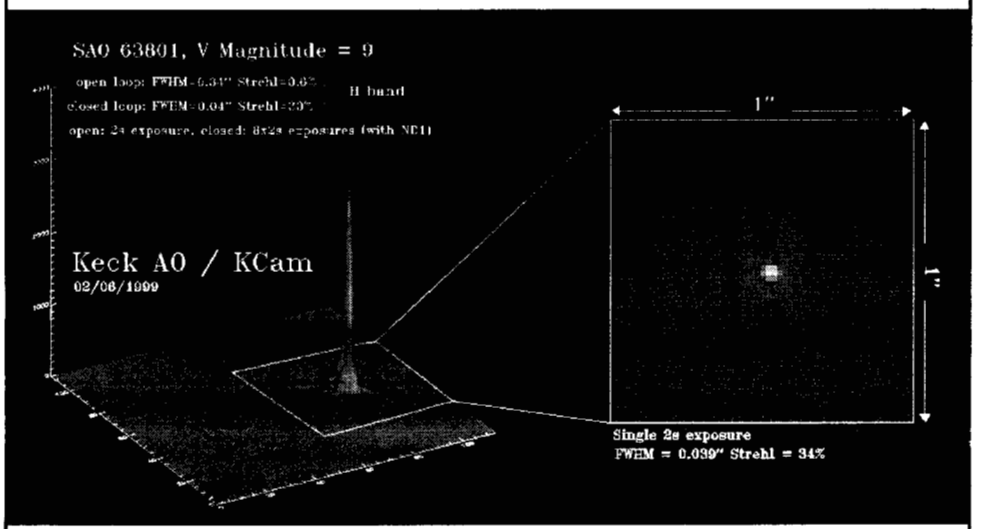
1st Light: V = 9 star



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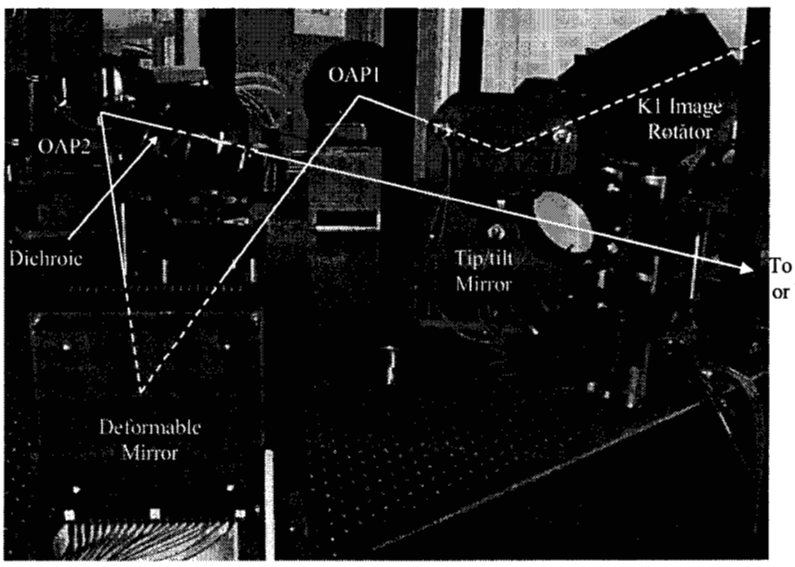
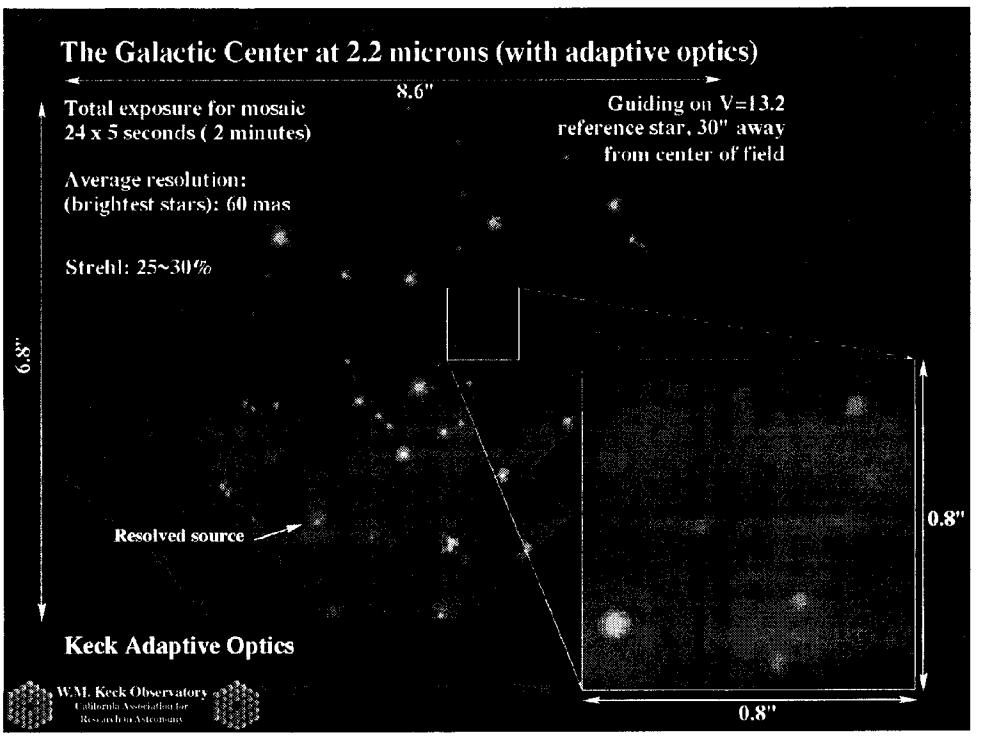
AO Science Path

- Science Path in Lab





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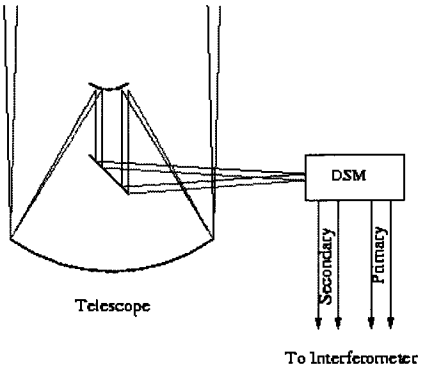
Dual Star Module



- Located at telescope Nasmyth focus
- Spatially separates two nearby stars for cophasing
- Feeds two collimated starlight beams into interferometer beam transport optics
- Includes constant term metrology endpoint
- Outriggers only:
  - Includes star acquisition pick-off optics
  - Includes pivot monitor for astrometry

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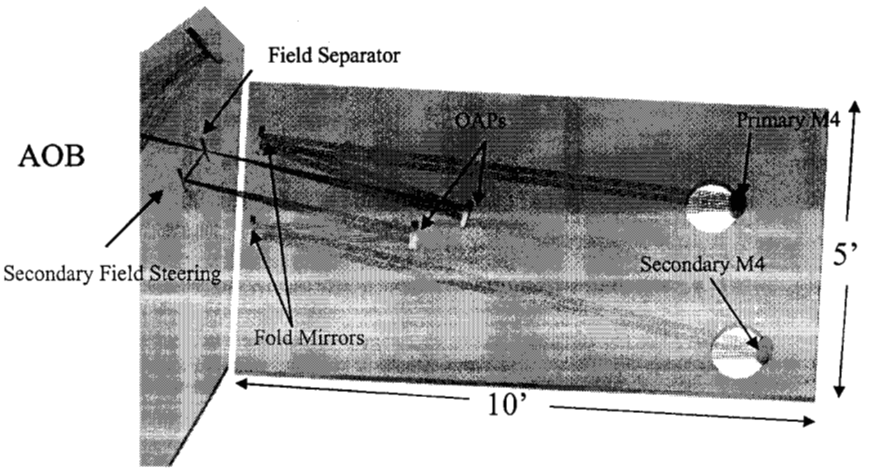
Keck DSM



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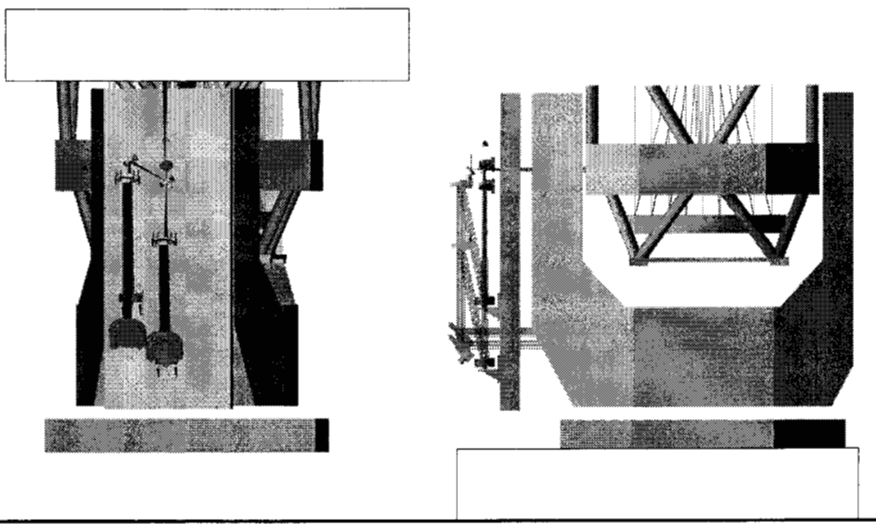
Outrigger DSM



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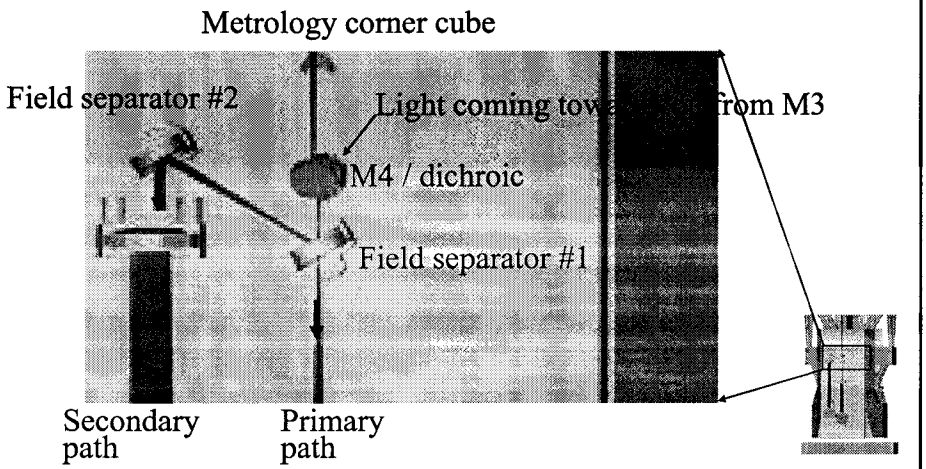
DSM Detail



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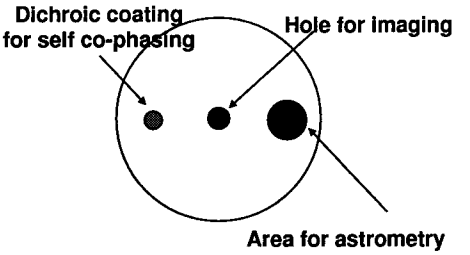
Optical Design: Field Separator

- Three modes
  - Astrometry
    - » Use high-index substrate for metrology continuity
    - » 20 arcsec radius FOV
  - Imaging
    - » Annular hole for high throughput
    - » 1 arcmin field
  - Self-cophasing
    - » On-axis only
- Solution: 3 co-mounted optics on field-separator mount
  - Translate to select mode



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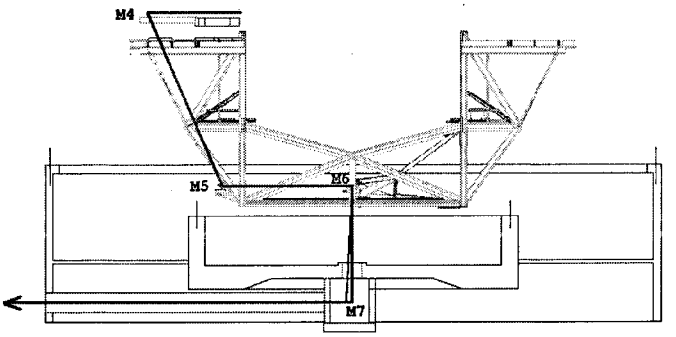
Coude Train and Beam Transport

- Keck coude train needs to be completed to bring light from DSM to base of telescope (M7)
  - Also need to derotate secondary beam
- Similar coude needed on outriggers
- Beam transport system routes light from M7 to delay lines in interferometry lab



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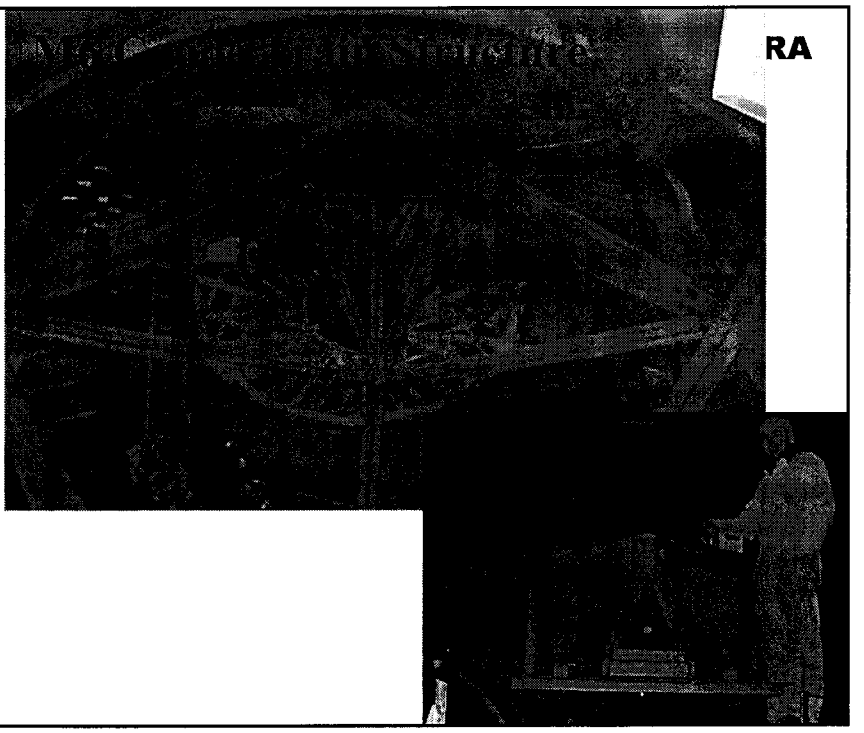

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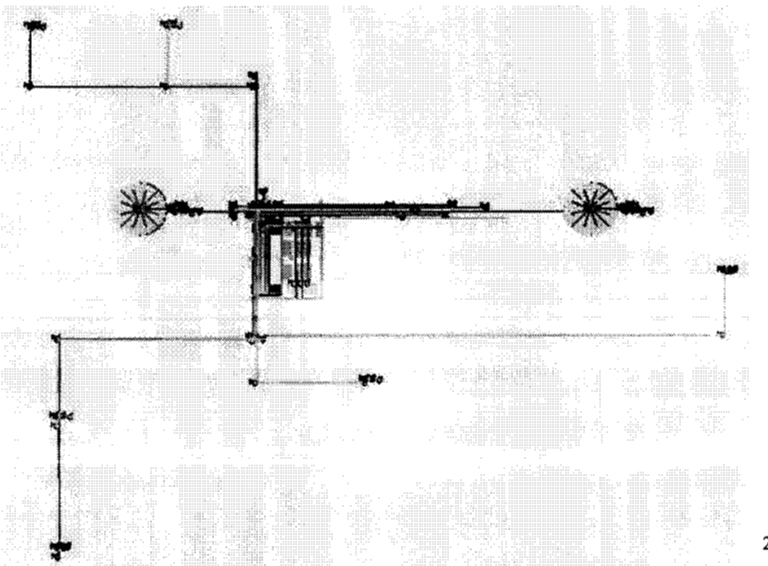
Site Overview



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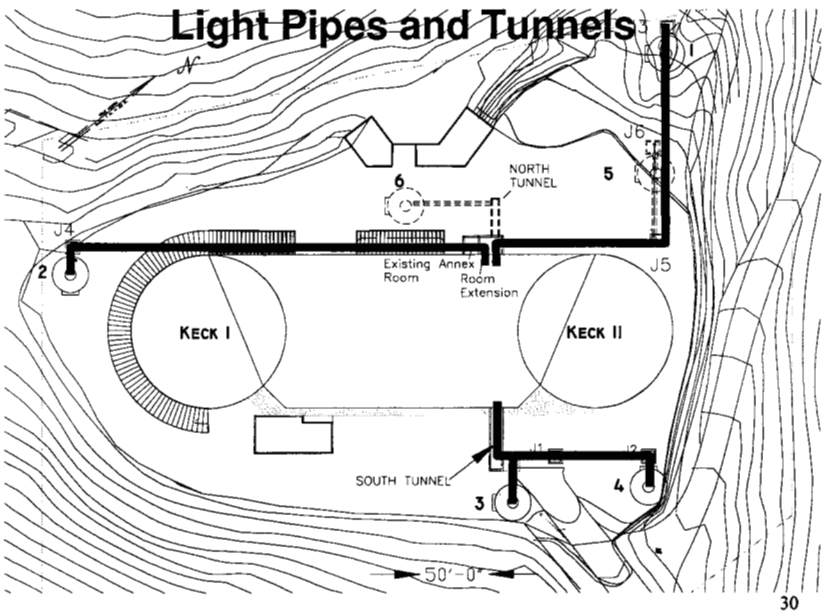
Light Pipes and Tunnels



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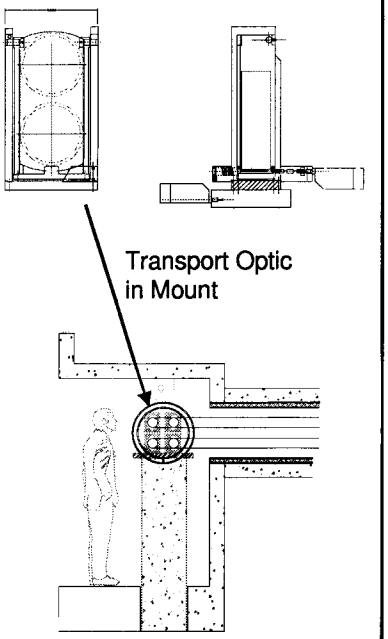
Transport Optics

- Transports star light from telescope bases to observatory basement
- Single mirror for primary and secondary starlight



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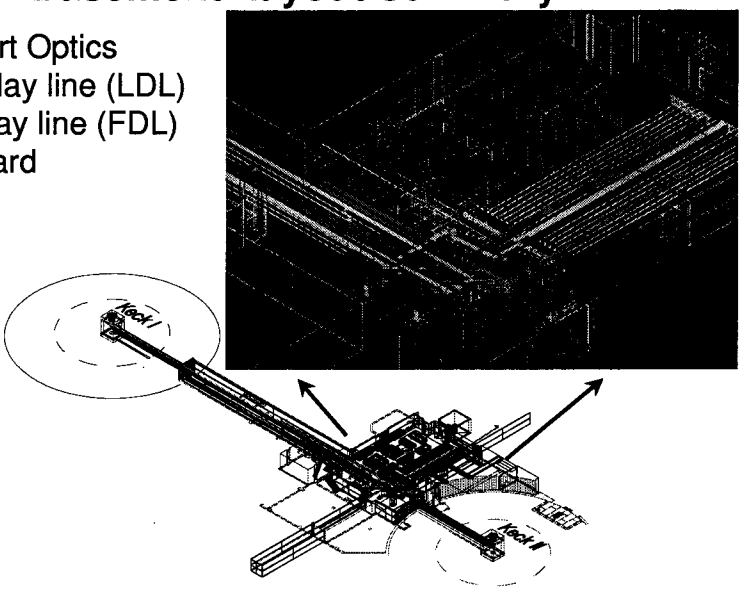
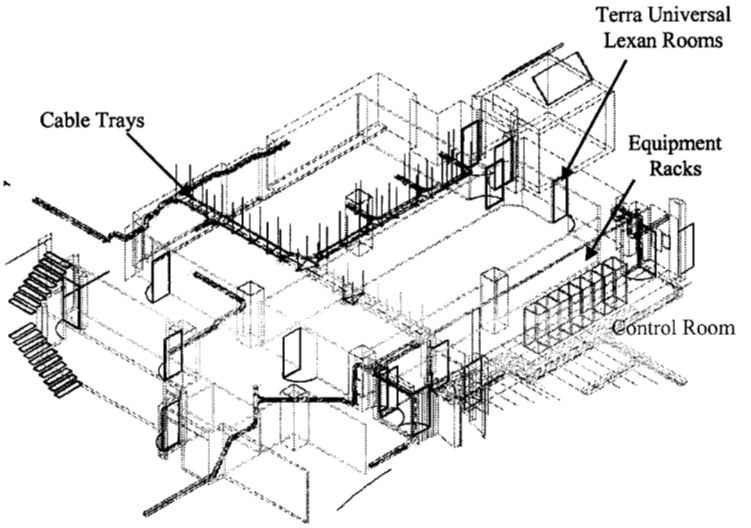
Basement Layout Summary

- Transport Optics
- Long delay line (LDL)
- Fast delay line (FDL)
- Switchyard



JPL **Isometric View of Basement Layout** CARA



K2

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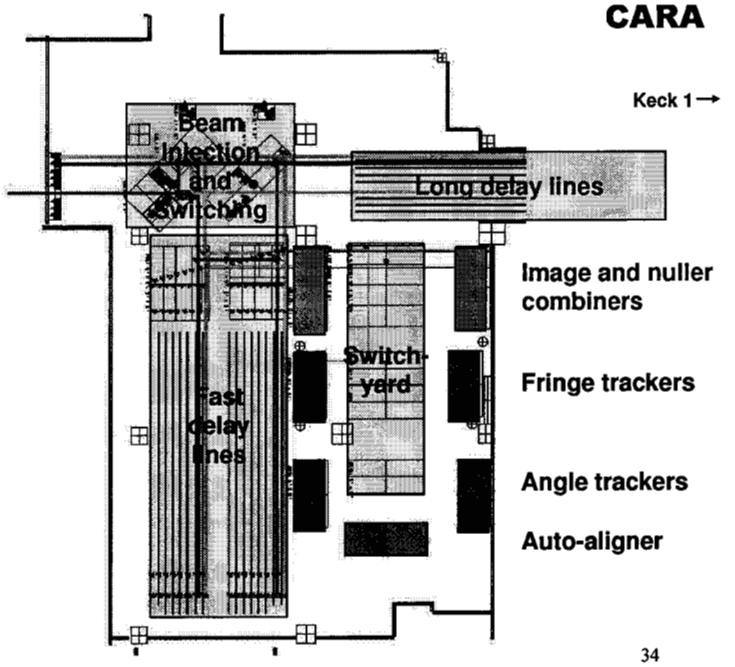
Basement Layout



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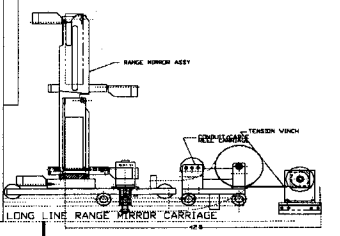
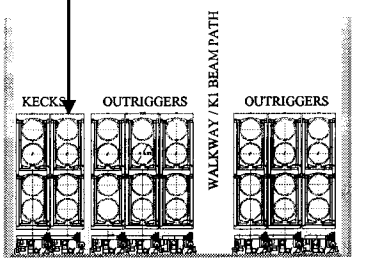
Long Delay Line

- LDL sleds move along coude tunnel in basement
  - 'Move and clamp' operation to provide delays up to 170 m
  - Stationary during an observation
  - Hold two 6"x14" mirrors - delays primary and secondary star identically



LDL Sled (1 of 6)



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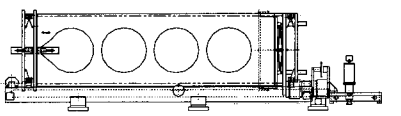
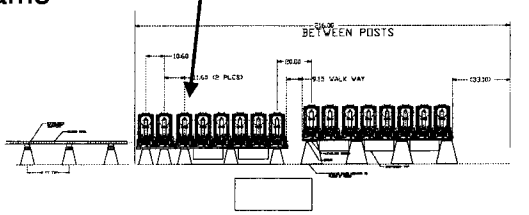
Fast Delay Lines (FDLs)

- FDL carts move along rails in basement
  - Continuous tracking of sidereal and atmospheric motion
  - 20 m delay range
  - 4 stage design, as on PTI
- Separate FDLs for primary, secondary starlight beams



FDL Cart (1 of 12)



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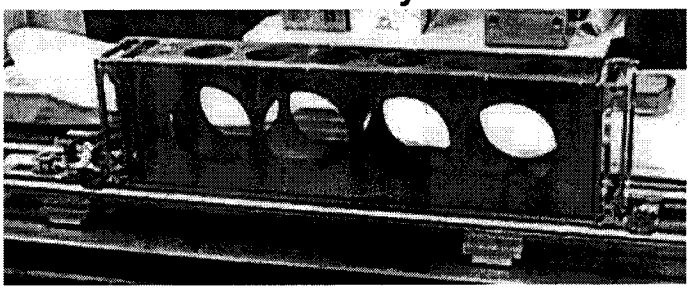
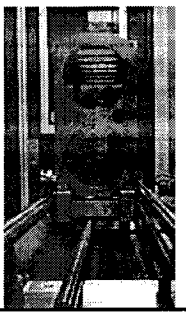
Fast Delay Line





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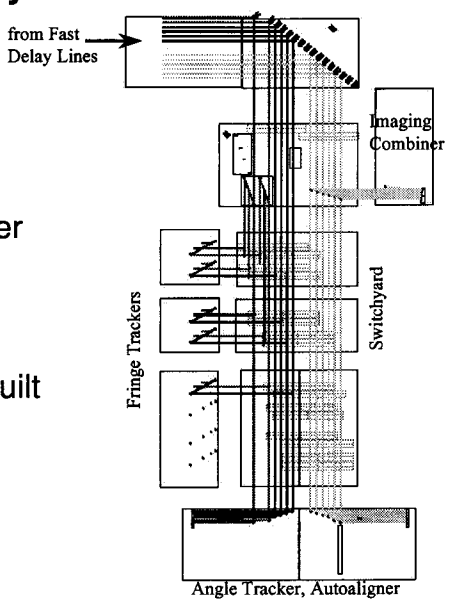
Switchyard

- Switchyard
  - Accepts 12 delayed starlight beams and directs to beam combiner for desired mode
- Stimulus
  - Star simulator to test all starlight subsystems - built into most combiners



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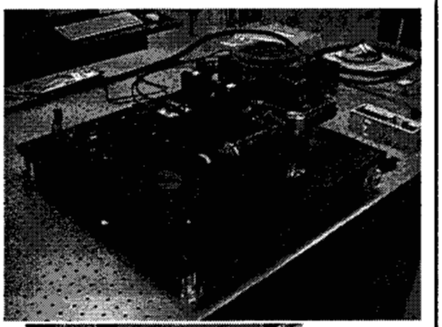
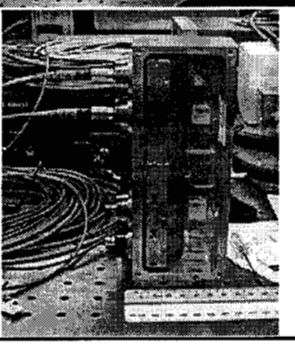
Laser Metrology

- Three types
  - Local metrology of delay lines for servo control
  - End-to-end metrology of optical path for astrometry and cophasing
  - Accelerometer sensing of common-mode telescope optics





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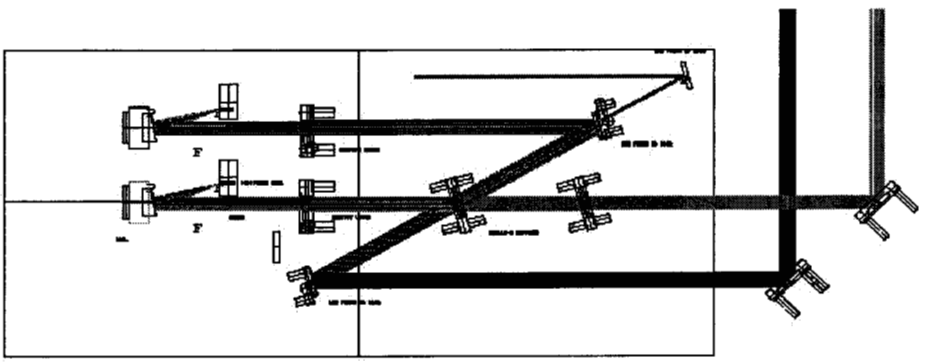
Fringe Tracker

- Five two-way 1.5-2.4-μm combiners support pair-wise telescope cophasing for all modes
- Combined light directed via optical fibers to Hawaii dewar



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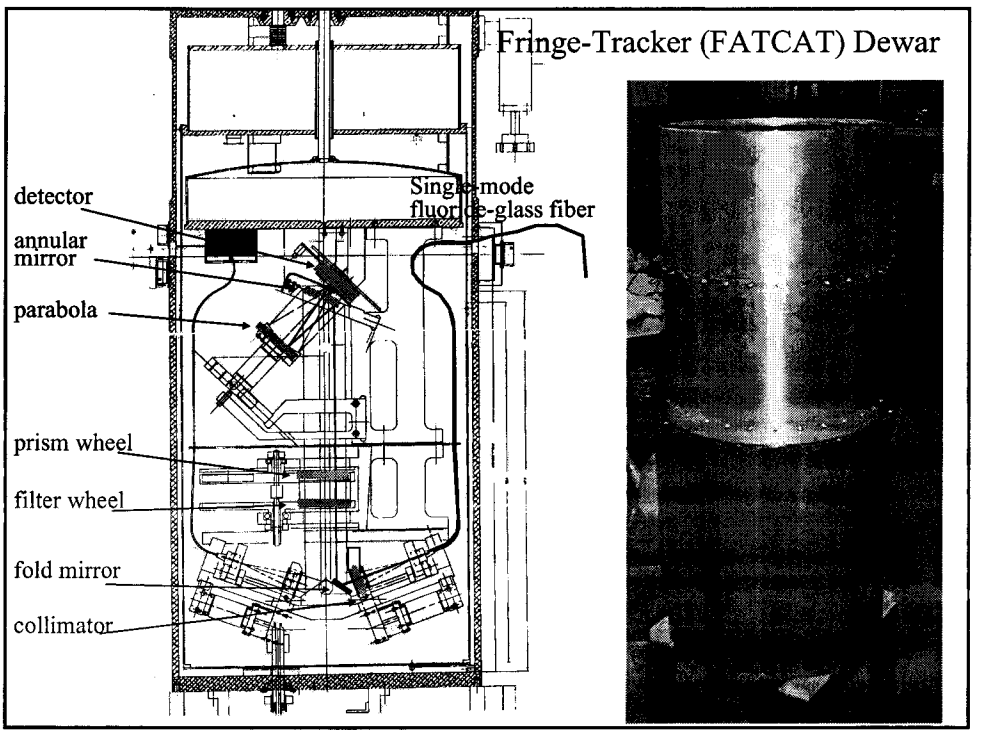

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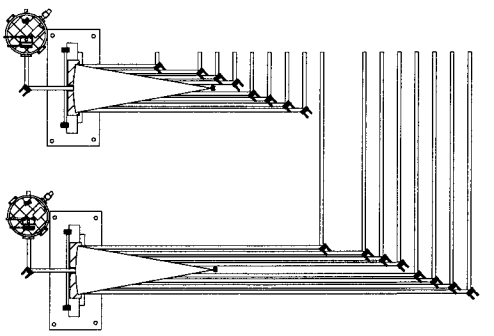
Angle Tracker

- For outriggers
  - Primary (high bandwidth) and secondary (low bandwidth with feedforward)
  - Correction via active secondary
- For Kecks
  - Track offsets to AO system
- Sensor
  - J-band infrared array
  - Separate dewars for primary and secondary stars



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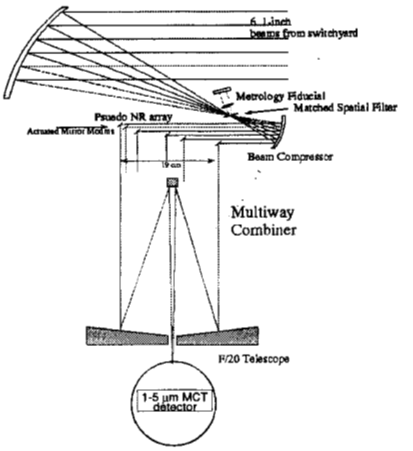
Multi-way Science Combiner

- Pair-wise measurements on up to 15 baselines simultaneously
- Non-redundant cross-dispersed image-plane combiner
- 1.6--5.0 μm coverage with mid-wave MCT array



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10 μm Nulling Combiner

- Primary instrument for exozodiacal characterization
- Uses achromatic nulling interferometer for high dynamic range measurement
- 10-μm infrared array camera

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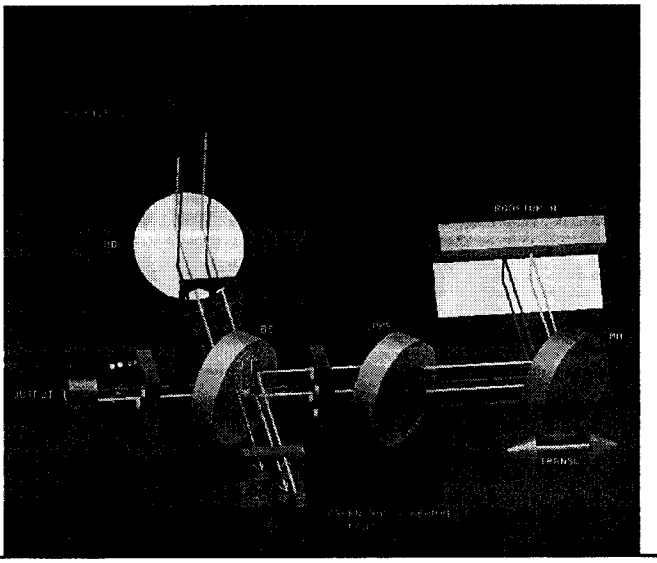
Interferometric Rooftop Nuller



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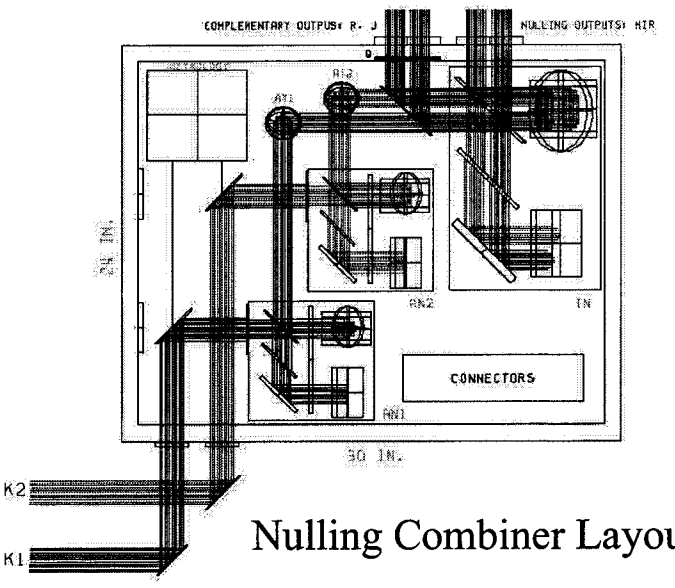

Nulling Combiner Layout

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Operating Modes

- Nulling for exozodiacal characterization
- Two-color differential-phase measurement
- Narrow-angle astrometry for detecting exoplanets
- Cophased imaging with 4, 5, or 6 telescopes

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Nulling: Measurement of Exozodiacal Dust

- Characterization of the exozodiacal emission around nearby stars
  - Goal: detection of a 10-solar-system equivalent zodiacal dust disk
- Information used for TPF mission planning
  - Large amounts of dust makes direct imaging of planets difficult
- Implement at 10 μm using the Keck-Keck baseline

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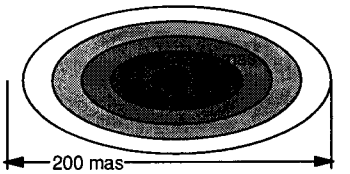
Detecting the Exozodiacal Signal

- Features of the problem
  - Strong light from central star
  - Relatively weak exozodiacal signal
  - Strong 10-μm background
- If background limited, SNR is good
  - The 1σ upper limit in 1 hour of integration is ~1 solar-system equivalent



Target at 10 pc

- Two nuller scales at 10 μm
  - Aperture: λ / diameter = 200 mas
  - Interferometer: λ / baseline = 25 mas

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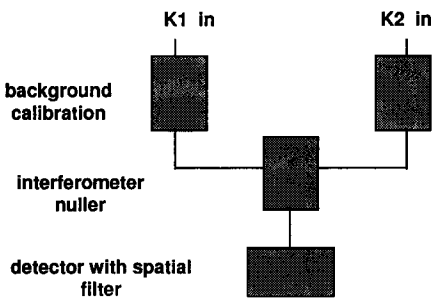
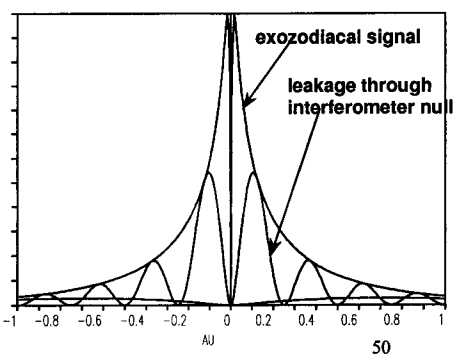
Detecting Exozodiacal Emission



- Nulling allows rapid chopping to allow background-limited detection
- Interferometer nuller attenuates star
- Single-mode spatial filter accommodates imperfect Strehl



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Differential Phase (Hot Jupiters)

- Scientific objectives
  - Direct detection of warm Jovian planets
    - » Characterize orbital parameters: Gives masses

Star	Orbit (AU)	T (K)	Sep. (arcsec)
HD 114762	0.40	475	0.014
υ And	0.05	1300	0.003
τ Boo	0.05	1400	0.003
55 ρ Cnc	0.11	900	0.008
16 Cyg	1.72	230	0.08
51 Peg	0.06	1200	0.004
70 Vir	0.43	450	0.019
ρ CrB	0.23	625	0.014
47 UMa	2.10	200	0.16

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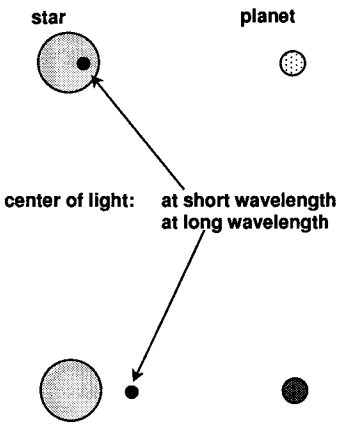
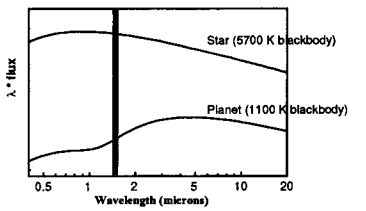
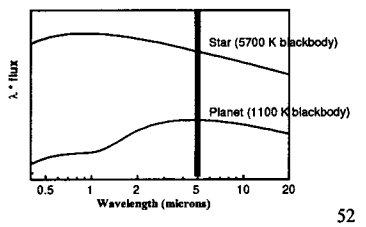
Detecting Hot Jupiters with Multi-color Observations







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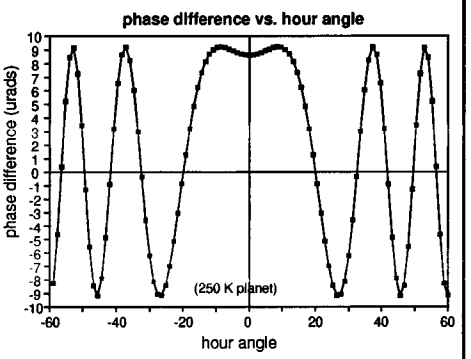
Detecting Hot Jupiters, more

- Interferometer measures fringe phase difference between two wavelengths
- Phase will vary with time as baseline and system rotate
- For some systems (GL229B), in-band structure will produce phase variations for small wavelength separations



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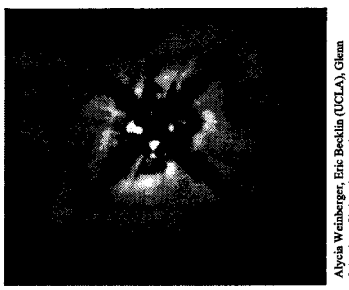
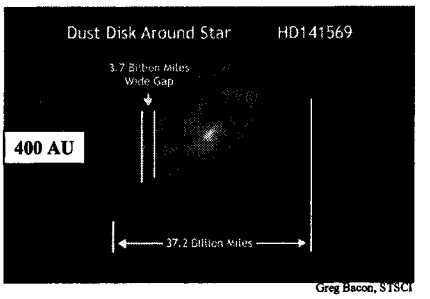
Imaging

- Science targets:
  - Protoplanetary disks
    - » Recent HST results consistent with the hypothesis that gaps form in dust disks (Weinberger et al. 1999)
  - Stellar surface, shells, accretion disks
  - Galactic center, stellar clusters
  - Solar system objects
  - AGNs



Alycia Weinberger, Eric Becklin (UCLA), Glenn Schneider (University of Arizona) and NASA



Greg Bacon, STSCI

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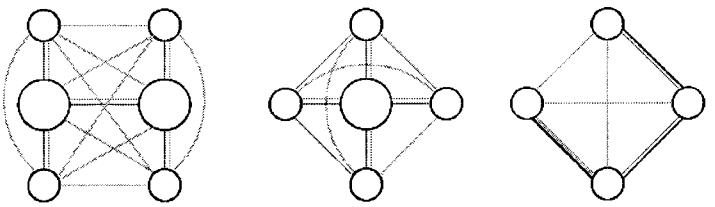
Imaging Modes

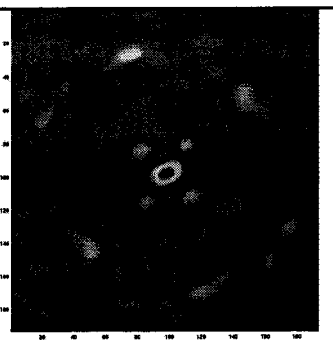
- Full array
  - Best sensitivity and spatial frequency coverage
- Single Keck array
- Outrigger only array
  - Limited sensitivity and spatial frequency coverage
  - Useful for brighter compact sources



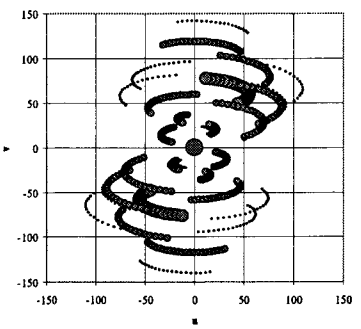
Science
Cophasing

Imaging Performance - Full array

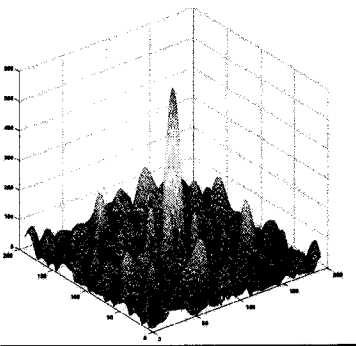
- **Baselines: 30 - 140 m**
- **Wavelengths: 1.5-5 μm**
- **Angular resolution: 3 mas at 2.2 μm**
- **Sensitivity: K=18 (point source, 1000 s)**



PSFs



K1K2+4 array (u,v) plane coverage:
HA=-4^h to +4^h, δ=19 deg. with dome blockage



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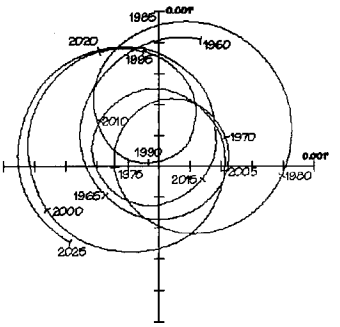
Narrow-Angle Astrometry

- Primary science: astrometric detection of planets down to Uranus mass from their reflex motion



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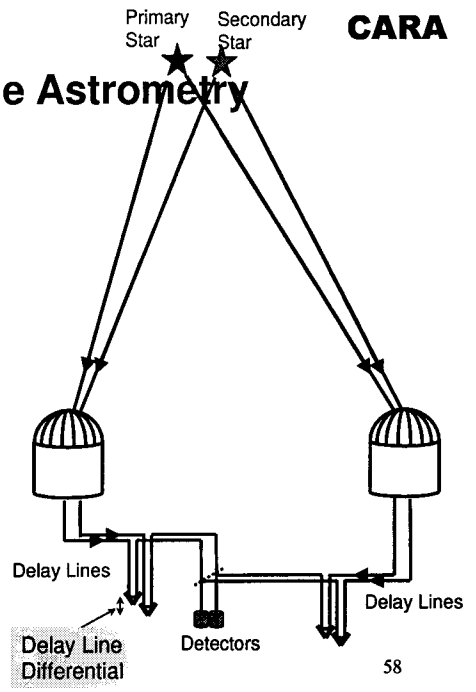
Narrow Angle Astrometry

- Primary star (target) - bright
  - Used to stabilize interferometer
- Secondary star - faint
  - Position reference
  - Located in same 'isoplanatic patch' as primary star
  - Long integration times possible
- Delay line position difference
  - Proportional to angular separation between stars
  - Measured with laser metrology
  - Wobble in separation indicative of unseen companion



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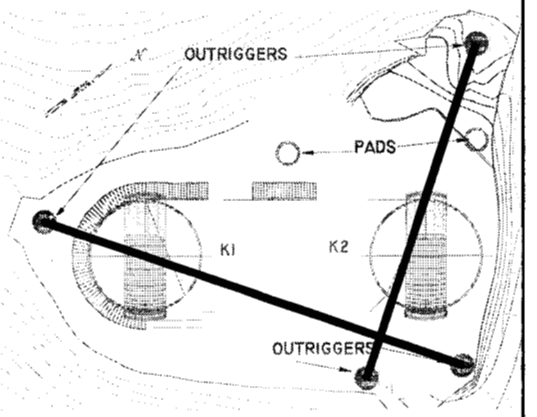
Astrometry Implementation

- Configuration
  - 4 1.8-m outriggers
  - Orthogonal >100m baselines
  - Dual star feeds
  - End-to-end laser metrology
  - 30 μas per hour accuracy for differential astrometry



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Configuration Summary

- All configurations have common aspects
  - Fringe tracking
    - » 2-μm fringe trackers
      - Closed-loop track on primary star
      - Feed-forward to secondary star's delay line
    - » "Science" detector
      - Closed-loop track on secondary star (varying bandwidths)
  - Angle tracking
    - » Isoplanatic correction using primary star
    - » Slow guiding using secondary star
  - Automated sequencing for control of delay line, switchyard, etc.

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Science Program

Program	Telescopes	Starting	Duration
Hot Jupiters	Kecks	2001	2-3yrs
Exo-zodiacal dust	Kecks	2001	2-3yrs
Astrometry	Outriggers	2003	>5yrs
Imaging	Full array	2003	Ongoing
Guest investigator	Any	2003	Ramping up

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